9.5 CENTURY-SCALE SOLAR VARIABILITY AND THE INSTRUMENTAL TEMPERATURE RECORD

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1. INTRODUCTION

Variability of the total solar irradiance (TSI) is a potential contributor to changes in global mean temperature on time scales longer than the relaxation time of the upper ocean (i.e. a few years). Indeed, striking correlations between the global instrumental temperature record, extending back a little more than a century, and observable solar features, most notably the solar cycle length, have led many investigators (e.g. Friis-Christensen 1991, Reid 1991) to postulate that solar variations may control decade-to-century (Dee-Cen) changes in global mean temperature T_s. In the absence of a convincing physical link between the observed solar features and TSI, however, the role of solar variability in the terrestrial climate record is difficult to quantify. In this study, we examine the implications of some simple physical assumptions regarding solar variability for the way it might affect the instrumental record of T_s.

2. MODELS OF SOLAR VARIABILITY

TSI variations on the order of 0.1 % have been detected within a solar cycle by satellite-borne radiometers (e.g. Willson and Hudson 1991) and successfully modeled in terms of observable photospheric features (e.g. Foukal and Lean 1990, Lean 1991). While their effect may be detectable in records of oceanic mixed layer and land surface temperatures (White et al. 1997, Stevens and North 1996), these sub-decadal fluctuations are too small to account for a significant fraction of the 0.5 'C increase in T_s which has been recorded over the last century (IPCC 1996). Cycle-to-cycle variability in TSI is most plausibly linked to longer-period variations in the convective transport of heat from the solar interior to the photosphere (e.g. Baliunas and Jastrow 1993, Hoyt and Schatten 1993), which may be detectable through its concomitant effects on observable solar features. In particular, Hoyt and Schatten argue that an increase in the turbulent eddy velocity associated with more intense convection leads to a more rapid decay of individual sunspots and a shorter solar cycle, thereby accounting for the correlation between cycle length and TSI hypothesized by earlier investigators.

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Here, we investigate the implications of this assumption for solar effects on the instrumental temperature record, using simplified models for cycle-to-cycle TSI variations and the response of the terrestrial mean temperature T_s to radiative forcing. " We model variations in the convective transport of heat F(t) to the photosphere as proportional to the decay rate of the solar cycle, defined as the reciprocal of the time elapsed between a solar cycle maximum and the subsequent minimum:

$$F(t_m) = k_1 / (t_m - t_M) \; ; \qquad (1)$$

here t_m and t_M are the epochs of a solar minimum and the previous maximum, and k_1 is a proportionality constant. The convective anomaly is defined at the time t_m of solar minimum, when the photospheric features associated with intracycle TSI variations are largely absent (e.g. Lean 1991).

Rather than applying an arbitrary smoothing to the solar record, which can considerably alter its climatic impact (Kelly and Wigley 1992), we choose to model the effect of convective heat flux variability on TSI in terms of a first-order autoregressive (AR1) process:

$$dW/dt + W/\tau = k_2 F(t) \; ; \qquad (2)$$

here τ is a relaxation time for solar convective anomalies, k_2 is a "scale factor, and $F(t)$ is the convective transport, linearly interpolated between the solar minimum data points $F(t_m)$. The relaxation time was estimated by choosing the kinematic eddy viscosity of the convective zone near the lower limit of a plausible range (v -1012-1013 cm^2s^{-1}) specified by Nesme-Ribes and Mangeney (1992), with the relevant length scale taken to be the depth of the convective zone (about 1/3 solar radius, L -.2'1010 cm), so that

τ - L^2/ v -12.6 years.

The resulting time series for TSI anomalies is shown by the solid line in Fig. 1, in arbitrary units; note that, due to the linearity of the AR I process, the proportionality constants k_1 and k_2 in Eqs. (1) and (2) can be combined into a single scaling factor. For comparison, the TSI anomaly computed by assuming that the convective flux F(t) is inversely proportional to the cycle length, defined as the interval between successive minima, is also shown (dashed line). While the cycle-length model has a clear upward trend over the 140-year span shown in the figure, the decay-rate model shows a sharp increase between 1880 and 1937, with the model's TSI subsequently decreasing to values below the 140-year average. The implications of these characteristics of the modeled TSI for climate variability are explored in the next section.

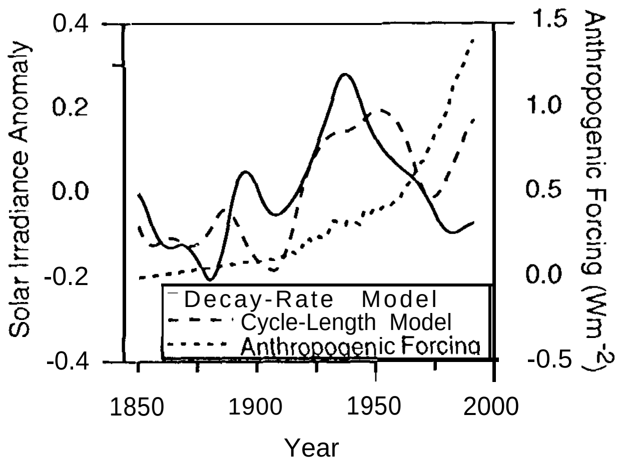

Figure 1. TSI variations produced by the solar models (arbitrary units, left ordinate) and the net anthropogenic radiative forcing (right ordinate).

3. GLOBAL MEAN TEMPERATURE RESPONSE

We employ a simplified version of the IPCC upwelling-diffusion model (Kattenberg et al. 1996), in which no distinction is made between land and ocean or northern and southern hemisphere, to compute the response of the global mean temperature T_s to changes in radiative forcing. A fraction Π = 0.2 of the temperature change is assumed to be downwelled by the thermohaline circulation, which is characterized by a fixed, globally averaged upwelling velocity of 4 m/yr. To explore the possible role of solar forcing in explaining Dec-Cen variations in the Jones et al. (1986) instrumental record of T_s that spans 1854- 1991, an ensemble of runs was performed starting from an assumed zero temperature anomaly in 1850, in which the amplitude of the net radiative forcing due to solar effects was varied from 0.2 to 1.4 Wi"2 (corresponding to a maximum TSI change of about 0.6'%. over the time interval studied), while the climate sensitivity was allowed to vary from 1.5 ^oC to 4.5 'C for a doubling of atmospheric C02 concentration. These results are presented in Fig. 2. The results of another series of runs, in which anthropogenic radiative forcing (IPCC 1996) was added to the modeled solar input, are presented in Fig. 3.

The cycle decay-rate (CD) model for TSI, which fails to show a positive trend during this century (cf. Fig. 1), is able to capture only a modest portion (up to 30%) of the observed temperature change, for climate sensitivities up to 4.5 'C (Fig. 2a). Although the best-fit model temperature simulates the observed variation up to 1976 fairly well, the rapid temperature increase since then is not captured (Fig. 2c). In fact, if the observed temperature record is limited to the period 1854-1976, the variance explained by the CD model nearly doubles (Fig. 2b); for an assumed sensitivity of 4.5 ^oC and a solar forcing of 0.9 Wi"2 (~0.4% TSI) the model captures 55'% of the observed variance, with considerable agreement evident down to decadal time scales (Fig. 2d).

The cycle length (CL) model, which displays an overall positive trend during the 20th century (Fig. 1), explains a larger fraction of the temperature variance (55%) over the full record (Fig. 2e) than the CD model, in particular capturing some of the upturn since 1976 (Fig. 2g). In this case, dropping the last 15 years produces only a small improvement in the fit to the observed record; over the time span 1854-1976, in fact, the best-fit CL model (Fig. 2h) explains only 1% more variance than the CD model, albeit at a more plausible value of the climate sensitivity (2.5 'C).

In order to understand how solar and anthropogenic influences combine to produce Dec-Cen changes in the instrumental temperature record, the above experiments were repeated while adding the radiative forcing produced by anthropogenic greenhouse gases and sulfate aerosol to the CD and CL series of Fig. 1; the aerosol series is scaled to produce a global-mean forcing of -0.6 Wi"2 in 1990 and the TSI now varies between O and 1.2 Wi"2. With the addition of anthropogenic forcing, the CD model is able to capture the positive trend which dominates the full temperature record, accounting for 72% of the 1854-1991 variance with a best-fit climate sensitivity of 3.0 'C (Fig. 3c). In this case, dropping the last 15 years degrades the correlation between the model and observed records (compare Figs. 3a and 3b), so that the best-fit simulation for 1854-1976 (Fig. 3d) captures only 3% more variance than the solar-only case (Fig. 2d), although the climate sensitivity (2.5 'C) is more realistic.

The results for the CL model forced with both anthropogenic and solar input (Figs. 3e-h) are quite similar to those with the CD model (Figs. 3a-d): the variance captured in both the full and truncated records is only very slightly less. It is interesting to note, however, that the CD model, whose TSI has a low correlation (0.06) with the anthropogenic forcing (cf. Fig, 1), produces fairly well-constrained estimates of the climate sensitivity and solar forcing (Fig. 3a) that are consistent with the observed temperature record (as used in Fig. 3c). For the CL model, on the other hand (cf. Fig. 1), the correlation between the two kinds of forcing

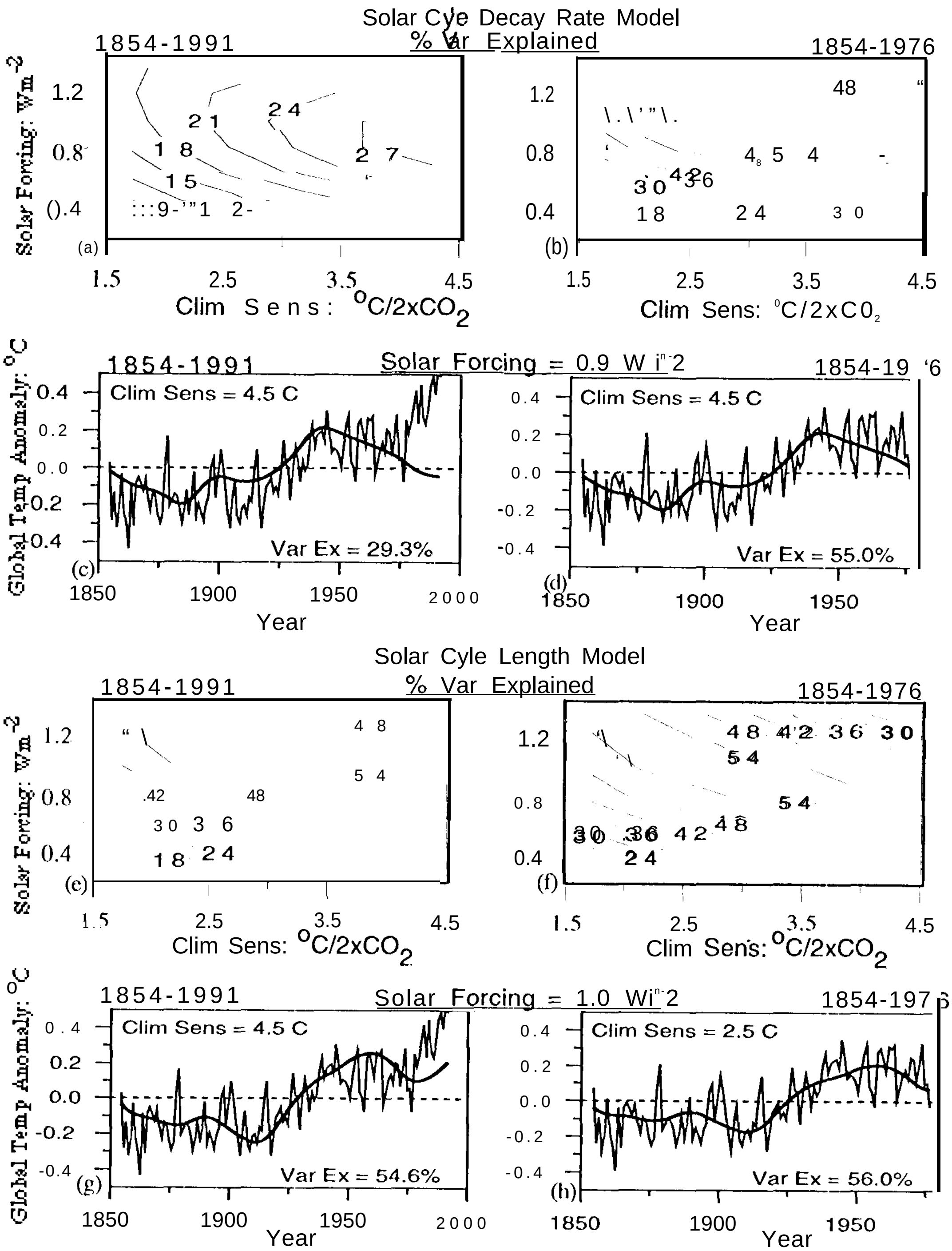

Figure 2. Comparison of simulations using an upwelling-diffusion model forced only by solar irradiance anomalies, with the global mean temperature series of Jones et al. (1 986). (a) Variance explained over the full length of the Jones et al. record, for solar anomalies computed from the cycle decay-rate model with amplitudes from 0.2 to 1.4 Wi^{n}2, and climate sensitivity from 1.5 to 4.5 ‘C; (b) as in (a), with the comparison restricted to 1854-1 976; (c) model (heavy line) and observed temperature anomalies for the best-fit parameters from (a); (d) as in (c), for the best-fit parameters from (b); (e) as in (a), for solar anomalies computed using the cycle-length (CL) model; (f) as in (b), for the CL model; (g) as in (c), for the best-fit parameters from (e); (h) as in (d), for the best-fit parameters from (f).

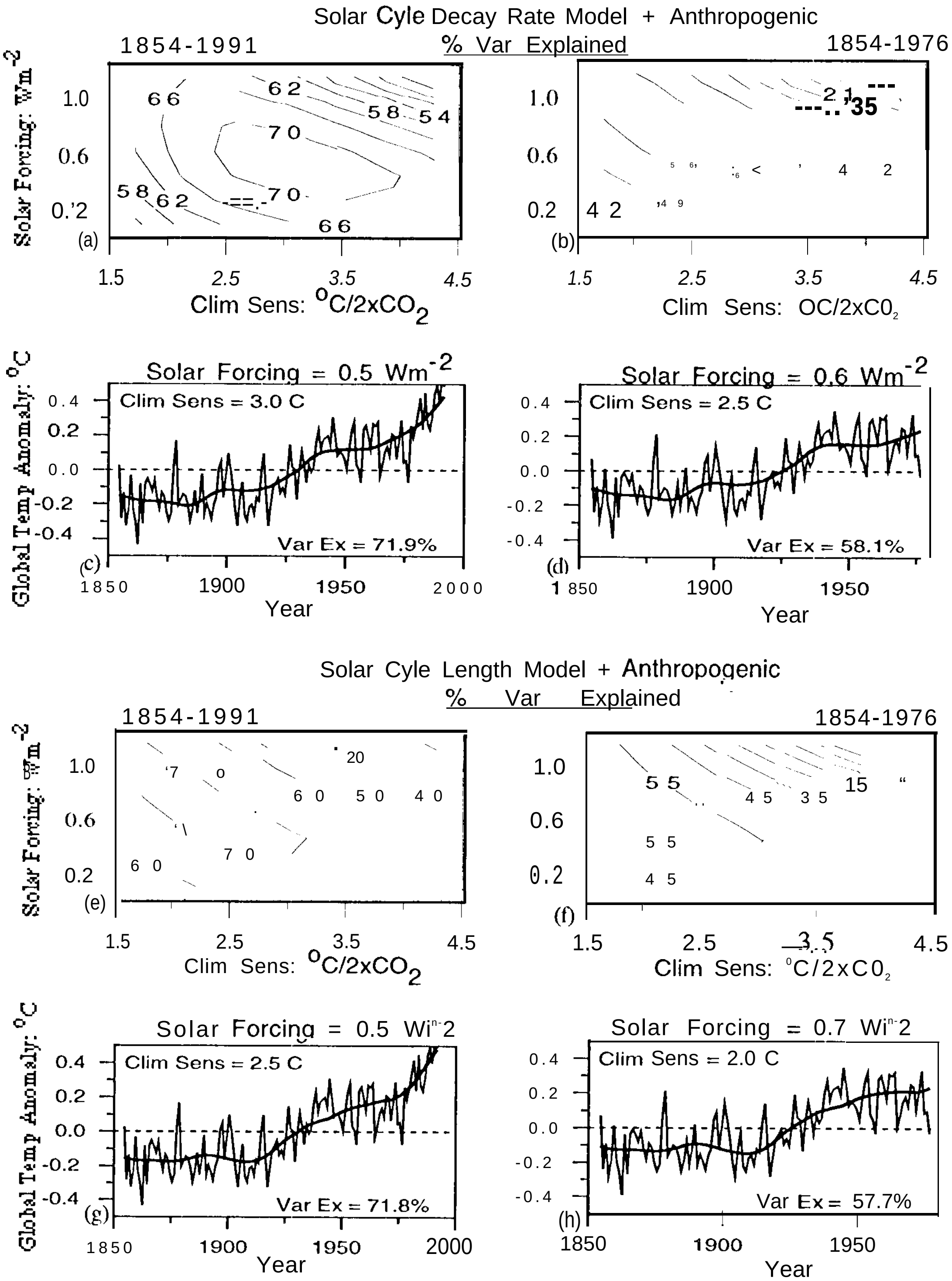

Figure 3. As in Figure 2, with a fixed history of anthropogenic forcing, incorporating sulfate aerosol effects scaled to have am lpude -0.6 Wi^{n}2 in 1990, added to solar irradiance anomalies with amplitudes varying from O to 1.2 Wm^{-2}. Note that comparisons of the full Jones et al. record with the simulations employing the cycle decay-rate model (Fig. 3a) permit more robust constraints to be placed on climate sensitivity and solar forcing amplitude than those obtained with the cycle-length model (Fig. 3e).

is relatively high (0.57), so that the effects of increasing climate sensitivity or solar forcing amplitude on the model temperatures are fairly similar; as a consequence, the comparison with the observed temperature record is less successful in constraining these two parameters (Fig. 3e).

4. CONCLUSIONS

Previous investigations have shown that models of total solar irradiance (TSI) based on variations in solar cycle length can capture a sizable portion of Dec-Cen changes in global mean temperature records. With the climate sensitivity restricted to values in the 1.5 -4.5 °C range, we find that a simplified upwelling-diffusion model with cycle-length (CL) forcing of amplitude 1.0 Wi"2 explains 55% of the variance in an observed global mean temperature series spanning 1854-1991, compared to 72% when anthropogenic forcing is added to the model. When the time span of comparison is restricted to 1854-1976, the variance captured increases only slightly (from 560/. to 58°/0) when anthropogenic forcing is added.

A more physically plausible proxy for intercycle variability is the solar cycle decay (CD) rate (e.g. Hoyt and Schatten 1993), which we model by assuming that convective heat transport anomalies are inversely proportional to the time between a solar cycle minimum and the preceding maximum. Whereas the CL model produces an upward irradiance trend during the present century, the CD model shows a pronounced maximum during the 1930s, with a subsequent decline to lower values in the fatter half of the century (Fig. 1). Consequently the CD model captures **only a small part (29%)** of the temperature variance over the full instrumental record, although for the 1854-1976 interval the variance it captures (55%) is only 1 % less than that for the CL model; when anthropogenic forcing is included, the CD model solution's variance (72%) is virtually identical to that produced by the CL model.

The main feature that distinguishes the CD from the CL modef is the former's "near-orthogonality" of its TSI variation to the anthropogenic forcing over the instrumental period (cf. Fig, 1). This feature results in more robust constraints (Fig. 3a) on the inferred climate sensitivity (--3.0 'C) and solar radiative forcing (--0.5 Wi"2, or a TSI variation over the instrumental period of about 0.2%) than are obtained from the CL results (Fig. 3e) when the full length of the Jones et al. (1986) record is employed Thus, improved modeling of solar physics and of the relationship it implies between TSI and observed photospheric properties, along with further clarification of the role of solar variability in the instrumental temperature record, can help constrain the Dec-Cen properties of the climate system.

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